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THEORETICAL CONSIDERATIONS GOVERNING THE DEHYDRATION OF FUELS BY GAS BLOWING

by

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ABSTRACT

The theory governing the removal of free and dissolved water by gas blowing is discussed and equations for predicting the performance of continuous counter current flow drying units are developed using a concept of "effective theoretical plates." From the general equation derived, it is shown that the performance of any particular fuel drying unit is dependent on the efficiency of the drying tower employed (effective number of theoretical plates), the ratio of the rates of gas to fuel flow used, the dryness of the inlet gas, the moisture content of the entering fuel and the temperature of operation. A number of solutions applicable to the dehydration of JP-5 fuel under a variety of operating conditions are included to demonstrate the relative importance of the above parameters and to illustrate the type of performance possible.

PROBLEM STATUS

This is a final report on this phase of the problem.

AUTHORIZATION

NRL Problem C01-01
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and NA 350-062

Theoretical Considerations Governing the Dehydration of Fuels by Gas Blowing

INTRODUCTION

Recently, the Bureau of Aeronautics has expressed interest in investigating the feasibility of incorporating some type of dehydration unit into systems which supply fuels to aircraft. Of various possible methods for drying fuels, one based on blowing with a dry gas seems to offer a promising approach and has been suggested by several activities as worthy of further study and evaluation. In addition, the petroleum industry has had long experience using air blowing processes to remove suspended water plus some dissolved water from certain products.

THEORETICAL CONSIDERATIONS

Reference (1) described the basic relations governing the exchange of water between hydrocarbon fuels and air. In particular, it was shown that fuels exchange water with air streams rapidly to reach an equilibrium value and that this equilibrium water content is equal to the product of the solubility of water in the fuel and the relative humidity of the air.

In the design of an operating unit, there are at least two basic processes that must be considered: (a) batch drying and (b) continuous counter current flow drying. Batch drying may be accomplished by the simple bubbling of dry gas through a tank of fuel. For further details governing such a process attention may be called to reference (1). Theoretical rate equations for such drying are developed in the mentioned report. Experimental data showed that even with simple equipment results were obtained which approached theoretical values. Continuous counter current flow drying inherently is more economical as far as gas utilization is concerned. In such a process, fuel would pass downward through a drying tower or column in which the drying gas would flow upward counter current to the fuel. Thus, there would exist a gradient of fuel dryness within the tower with wet fuel entering the top and the driest fuel exiting out of the bottom. With this system, the entering dry gas would be used to remove moisture from fuel that had already been exposed to drying in the preceding sections of the tower and a conservation of dry gas requirements would be effected.

The efficiency of a counter current flow drying tower can be measured in terms of "effective theoretical plates." Using this concept, it is possible to develop equations to predict the performance of any unit employing a tower having an efficiency of any given number of theoretical plates. The general and simplified equations for the performance of the drying process are derived in Appendix B. The simplified equation which is valid for all cases, except for the special condition where B=1, is:

$$C = \frac{C_o \ (B-1) + VW_o \ (B^n-1)}{B^{n+1} -1}$$

where

- C = water content of dried fuel exiting from tower, mg/liter
- C_o = water content of fuel entering tower, mg/liter
- C_s = water content of saturated fuel at temperature of operation, mg/liter
- W_s = water content of saturated gas at temperature of operation, mg/liter
- W_o = water content of inlet drying gas, mg/liter This value is W_s x RH, where RH is the relative humidity of the inlet gas at temperature of operation.
- V = volume ratio of gas to fuel flow rates (both rates must be expressed in same units; e.g. liters/min, gals/min etc.).
- n = efficiency of tower (number of effective theoretical plates
- $B = V \left(\frac{W_s}{C_s}\right)$

From the above equation it is seen that the performance of any particular fuel drying unit is dependent on the efficiency of the drying tower (effective number of theoretical plates), the ratio of the rates of gas flow to fuel flow used, the dryness of the inlet gas, the moisture content of the entering fuel and the temperature of operation. The relative significances of these parameters may be ascertained by solving the equation for various conditions and comparing the results graphically. Figures 1-6 of Appendix A include the results of a number of such solutions for the continuous counter current flow gas drying of a typical JP-5 fuel at 80°F. These curves include performances to be expected of drying units having towers of different numbers of theoretical plates using various gas to fuel volume ratios with gases of differing humidities. An inspection of the curves makes obvious the relative importances of each of these parameters. The given equation coupled with curves such as those given are basic to any counter current flow drying unit and should aid materially toward the design of an economical finished operating system.

Aside from removing dissolved water, a counter current unit will also remove finely divided entrained water. In this case, however, the efficiency of removal of dissolved water will be somewhat lowered and will depend on the quantity of free water present. Figure 7 of Appendix A shows the performance of a drying tower, of five theoretical plate efficiency, for the removal of water from fuels containing different levels of undissolved water.

ACKNOWLEDGEMENT

The author is indebted to Dr. H. A. Hauptman for reviewing the derivation of the general equation and for suggesting the development of the simplified versions.

REFERENCES

1. J. A. Krynitsky and H. W. Carhart, "The Exchange of Water Between Hydrophobic Liquids and Air," NRL Report 3874, December 3, 1951.

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Appendix A

Note: For convenience, the ordinates of the above figures have been converted from the c.g.s. units used in the equation to more common engineering terms.

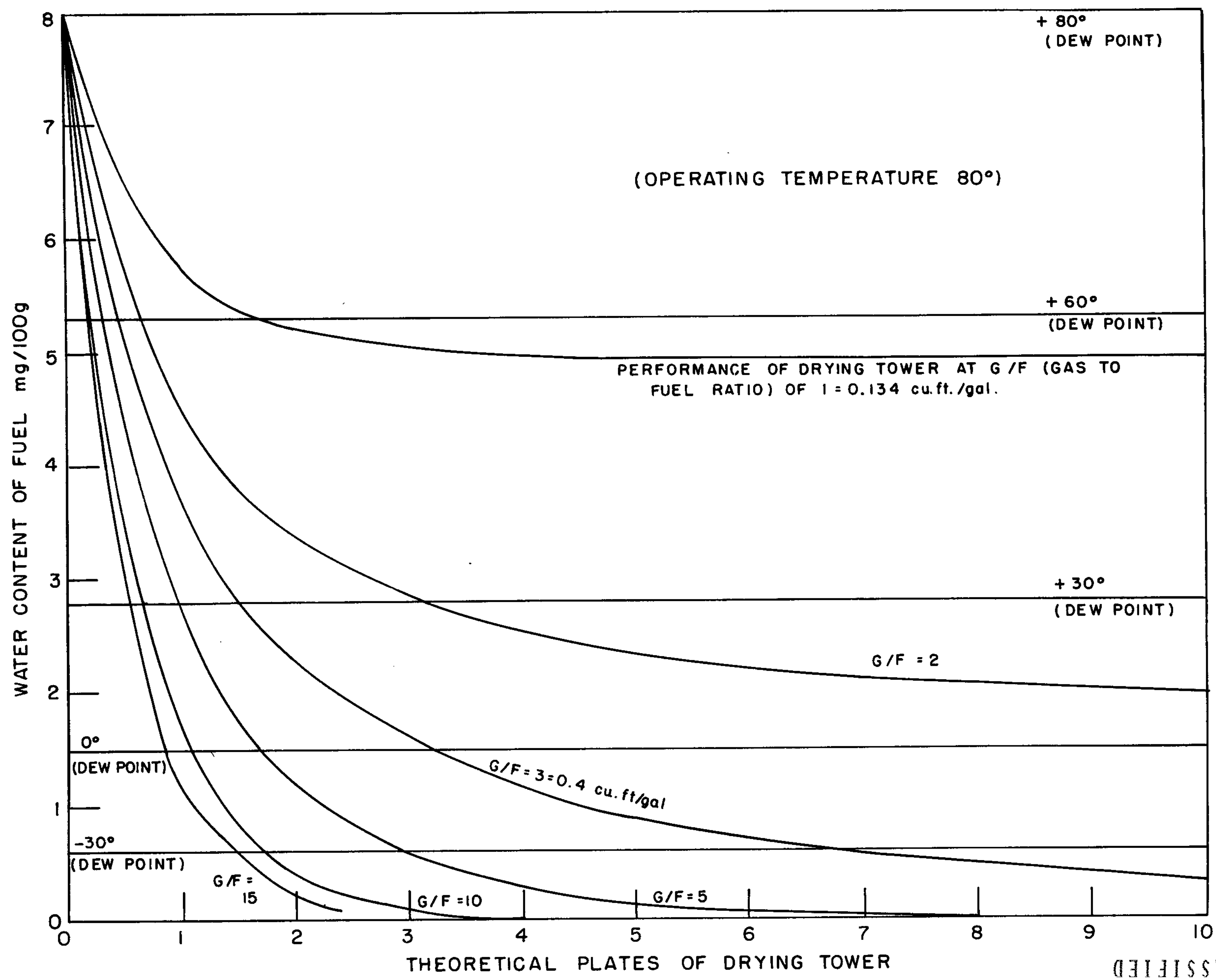

Figure 1 - Removal of Water as a Function of Drying Tower Efficiency and Gas to Fuel Ratio Using Gas at 0% RH

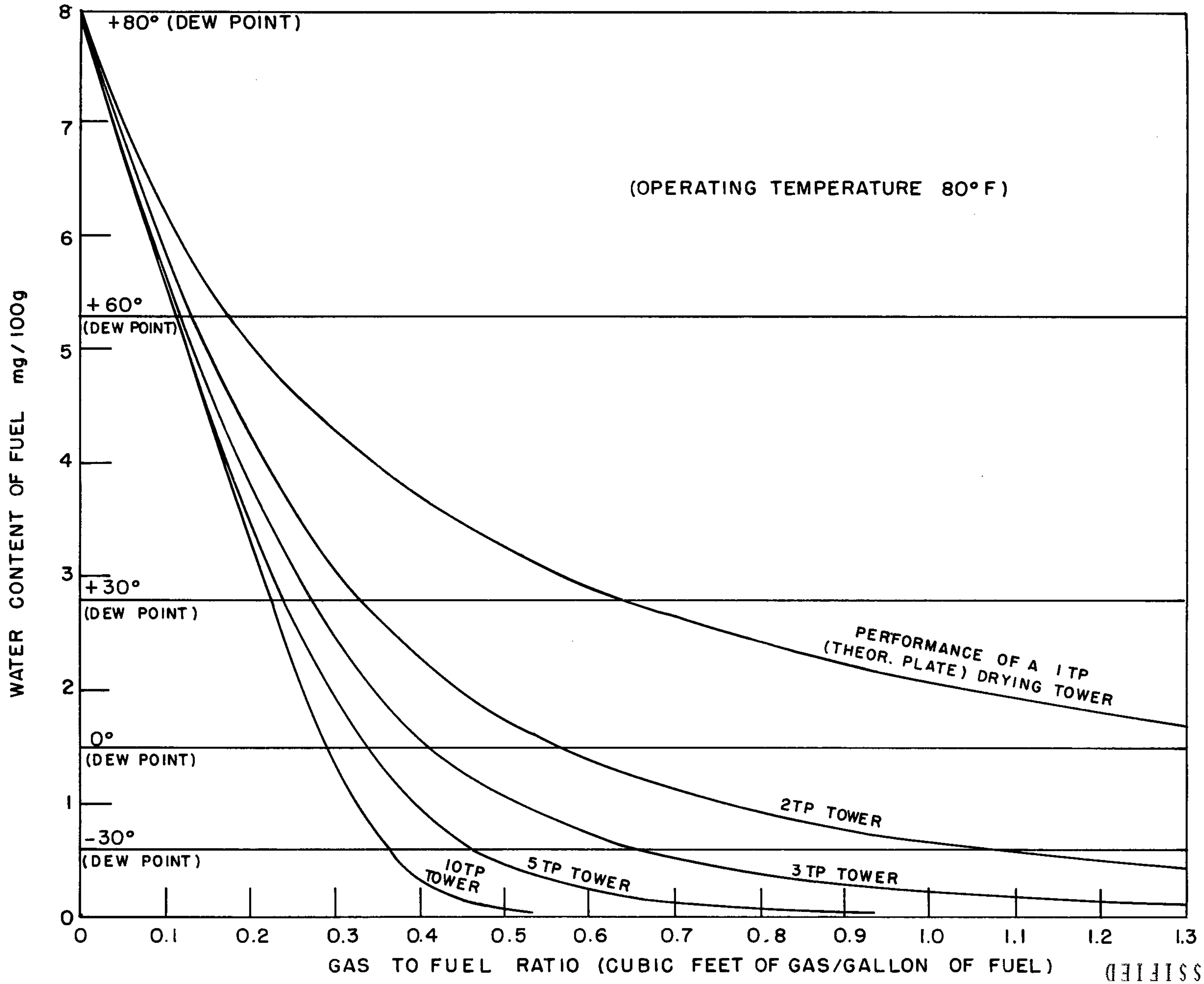

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Figure 2 - Removal of Dissolved Water as a Function of Drying Tower Efficiency and Gas to Fuel Ratio Using Gas at 0% RH

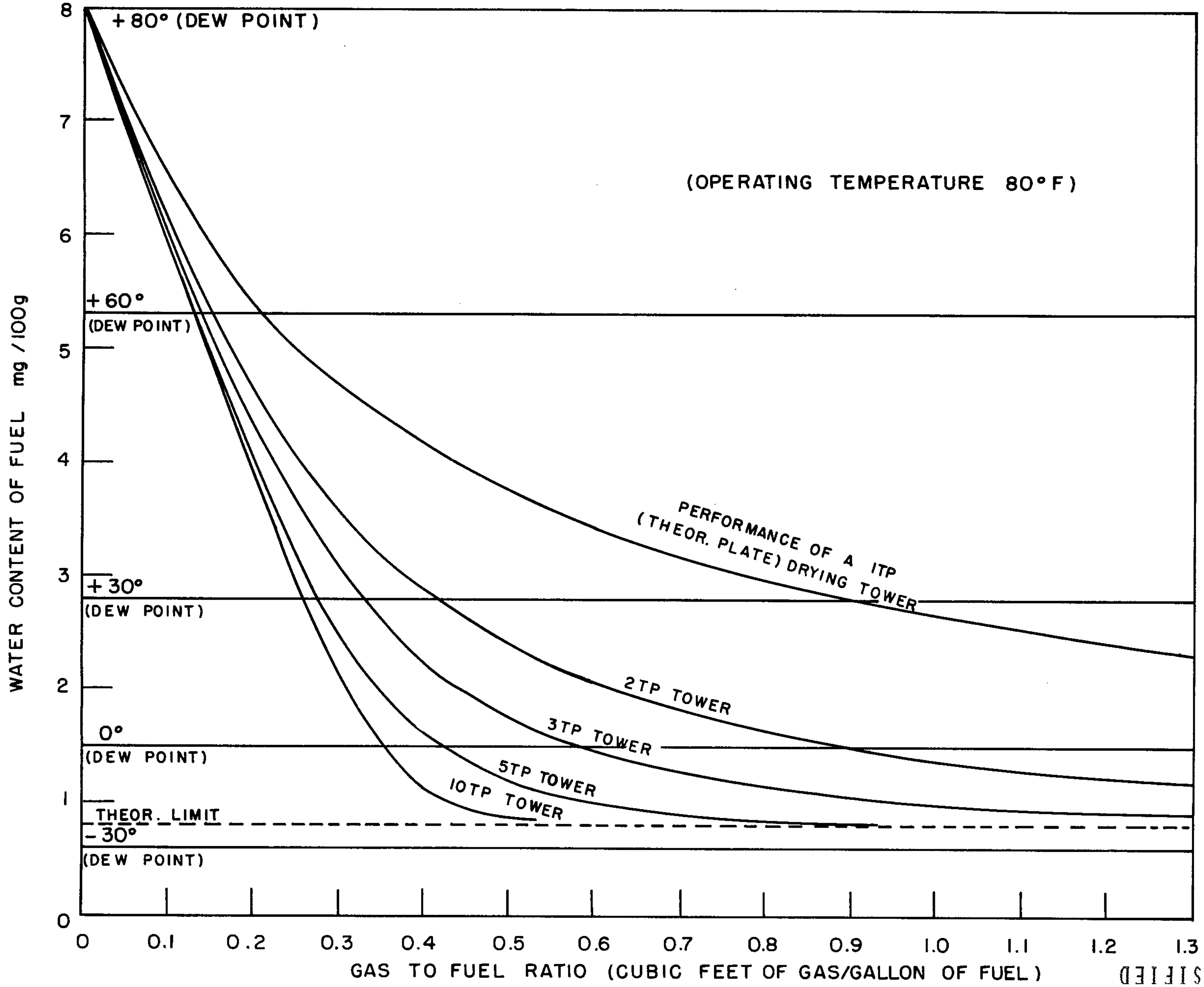

Figure 3 - Removal of Dissolved Water as a Function of Drying Tower Efficiency and Gas to Fuel Ratio Using Gas at 10% RH

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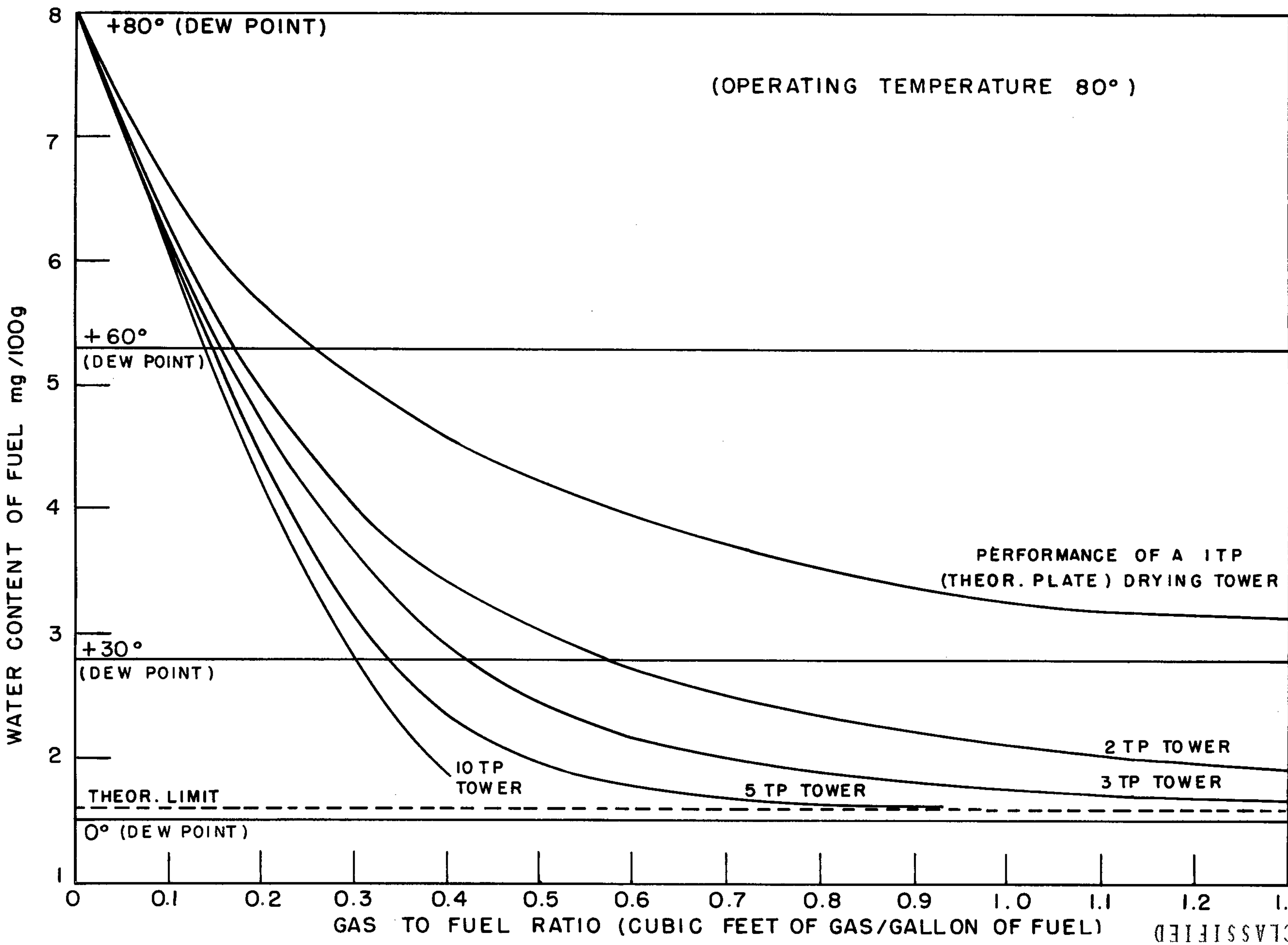


Figure 4 - Removal of Dissolved Water as a Function of Drying Tower Efficiency and Gas to Fuel Ratio Using Gas at 20% RH

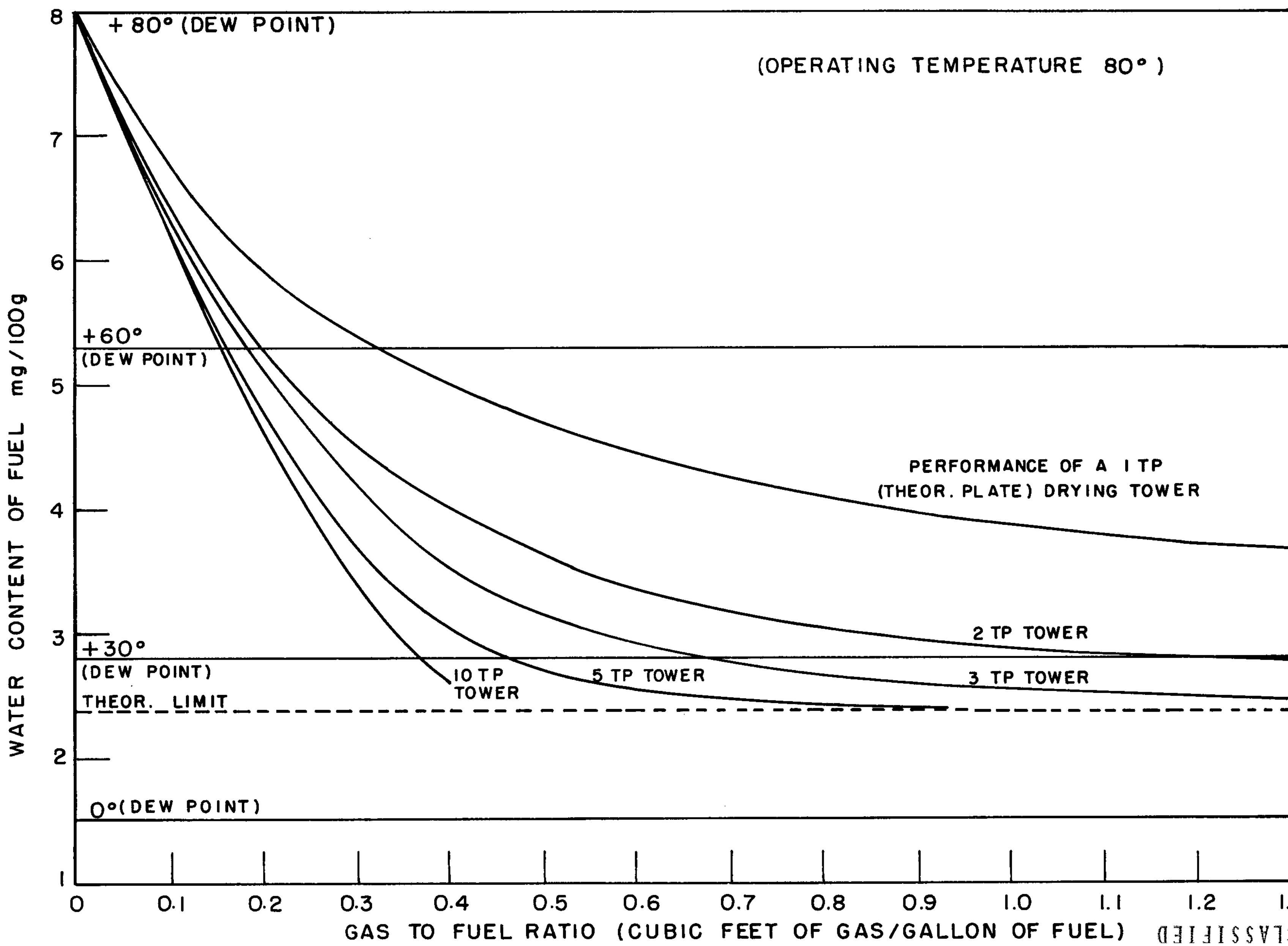


Figure 5 - Removal of Dissolved Water as a Function of Drying Tower
Efficiency and Gas to Fuel Ratio Using Gas at 30% RH

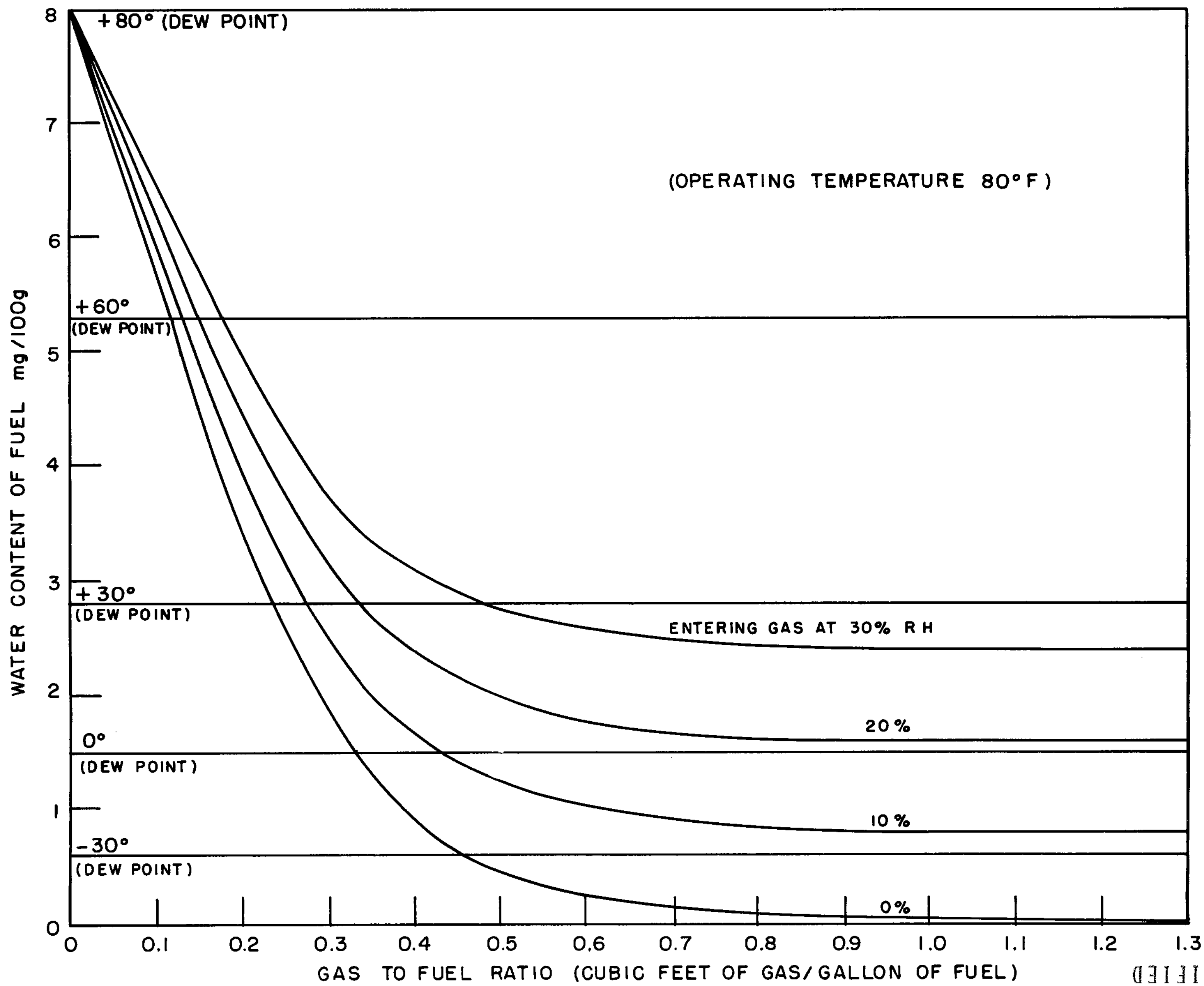


Figure 6 - Removal of Dissolved Water by a 5 Theoretical Plate Drying Tower as a Function of Gas Humidity and Gas to Fuel Ratio

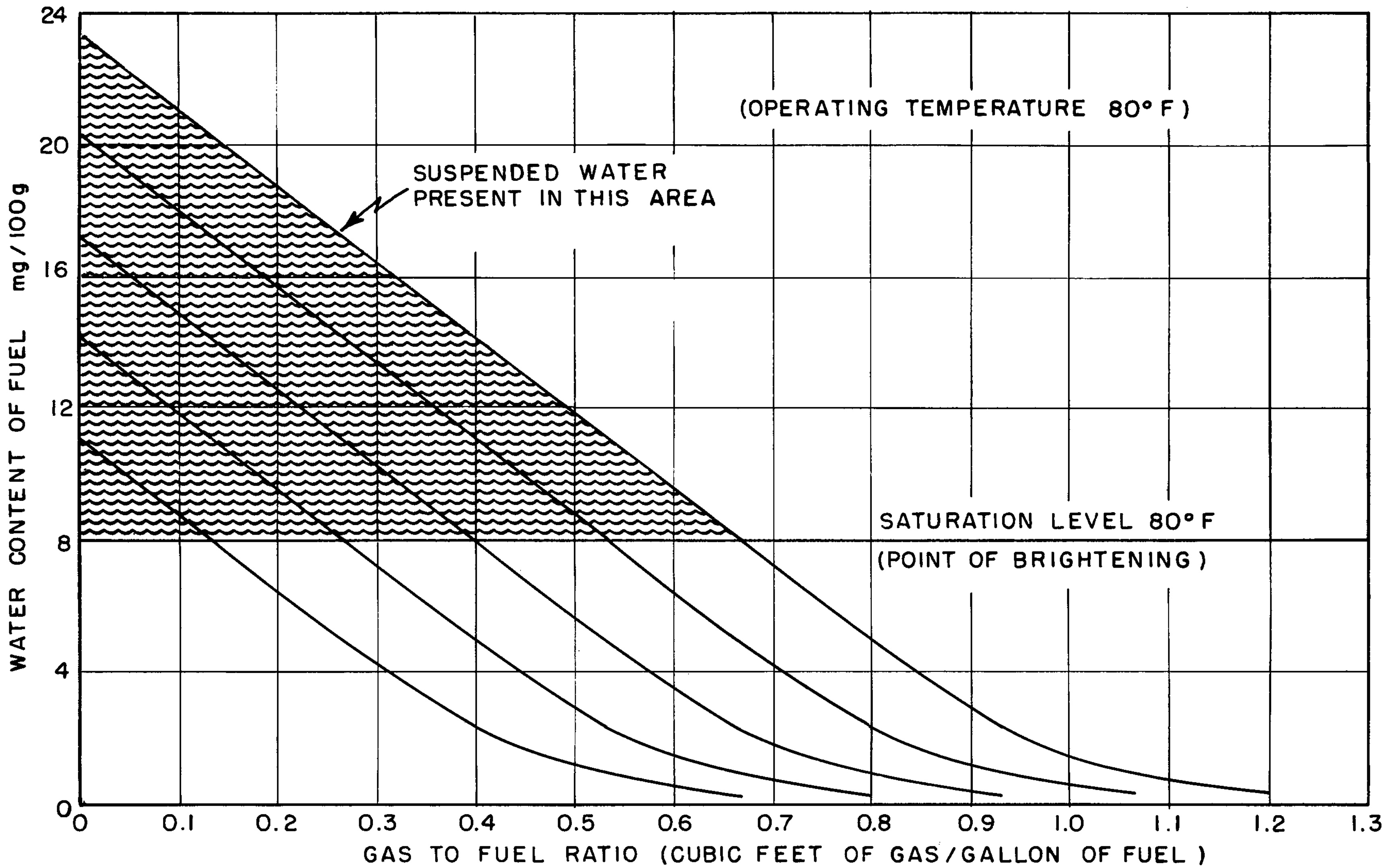


Figure 7 - Removal of Both Suspended and Dissolved Water by a 5 Theoretical Plate Drying Tower Using Gas at 0% RH (Curves for Different Initial Water Contents)

Appendix B

Derivations of Performance Equations For The Dehydration of Fuels by Gases Using a Continuous Counter Current Flow Process

Note:

(1) All water contents expressed in terms of mg/liter.

<u>Notations</u>:

T.P. = effective theoretical plate

C_o = water content of entering fuel

C_s = " " " saturated fuel at temperature of operation

C_1 = water content of fuel exiting T.P. #1

C_2 = " " " " " T.P. #2

C_n = " " " " " T.P. #n

C = " " " " " a drying unit

W_o = " " " entering gas

W_s = " " " saturated gas at temperature of operation

W_1 = water content of gas exiting drying unit

W_n = " " " " " T.P. #n

RH = relative humidity of gas at temperature of operation

v_f = rate of fuel flow through unit ⎤ expressed in same units;

v_g = " " gas " " " ⎦ e.g. liters/min

$V = v_g/v_f$

$A = C_s/W_s$

$B = V/A = \dfrac{W_s}{C_s} V$

Definition of Effective Theoretical Plate (T.P.)

A T.P. is defined as that length or portion of a continuous counter current flow drying tower or column from which the water contents of the exiting gas and exiting fuel would be at equilibrium with each other. In effect, the result achieved by a T.P. is the same as if the entering gas and entering fuel were allowed to stand in contact with each other and exchange water until equilibrium was reached.

Basic Consideration

The work described in NRL Report 3874 showed that when the water contents of a gas and a fuel are in equilibrium then the following relation exists:

$$\text{water content of fuel} = C_s \times RH$$

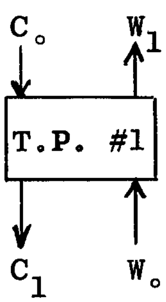
Therefore for any TP, n

$$C_n = C_s \times RH \text{ of gas exiting plate } n$$

but RH gas exiting plate n $= \dfrac{W_n}{W_s}$, also $\dfrac{C_s}{W_s} = A$

Hence $\boxed{C_n = AW_n}$ I and $\boxed{W_n = \dfrac{C_n}{A}}$ II

Equation for a 1 T.P. unit



The rate of water loss by fuel must equal the rate of water gain by gas

or

$$v_f\ (C_o - C_1) = v_g\ (W_1 - W_o)$$

since $v_g/v_f = V$

$$C_o - C_1 = V\ (W_1 - W_o)$$

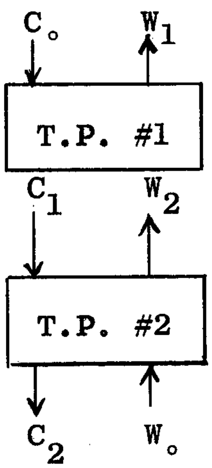
by equation II $W_1 = \dfrac{C_1}{A}$, so

$$C_o - C_1 = V\ \left(\frac{C_1}{A} - W_o\right)$$

Solve for C_1 and then substitute B for $\dfrac{V}{A}$

$$\boxed{C_1 = \frac{C_o + V\ W_o}{1 + B}} \quad \text{III}$$

Equation for a 2 T.P. unit



For this case C_2 may be solved in terms of C_1 and $W_\circ$ by relationship III

$$C_2 = \frac{C_1 + V\,W_\circ}{1 + B} \qquad \text{(a)}$$

Likewise C_1 in terms of $C_\circ$ and W_2 is

$$C_1 = \frac{C_\circ + V\,W_2}{1 + B}$$

but $V = A\,B$ and by I, $A\,W_2 = C_2$ so

$$C_1 = \frac{C_\circ + C_2\,B}{1 + B}$$

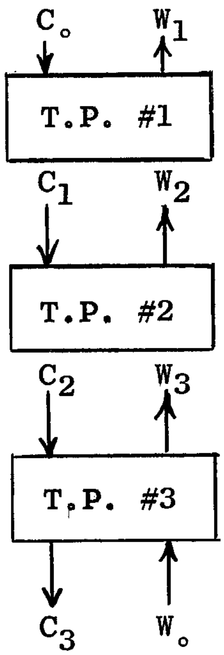
substitute for C_1 in equation (a)

$$C_2 = \frac{\left[\dfrac{C_\circ + C_2\,B}{1 + B}\right] + V\,W_\circ}{1 + B}$$

solve for C_2

$$\boxed{C_2 = \frac{C_\circ + V\,W_\circ\,(1 + B)}{1 + B + B^2}} \qquad \text{IV}$$

<u>Equation for a 3 T.P. unit</u>



Solve for C_3 in terms of C_2 and $W_\circ$ using relationship III

$$C_3 = \frac{C_2 + V\,W_\circ}{1 + B} \qquad \text{(b)}$$

solve for C_2 in terms of $C_\circ$ and W_3 using relationship IV

$$C_2 = \frac{C_\circ + V\,W_3\,(1 + B)}{1 + B + B^2}$$

but $V = A\,B$
and by I,
$A\,W_3 = C_3$

so

$$C_2 = \frac{C_\circ + C_3\,B\,(1 + B)}{1 + B + B^2}$$

substitute for C_2 in equation (b)

$$C_3 = \frac{\left[\dfrac{C_\circ + C_3\,B\,(1 + B)}{1 + B + B^2}\right] + V\,W_\circ}{1 + B}$$

solve for C_3

$$\boxed{C_3 = \frac{C_\circ + V\,W_\circ\,(1 + B + B^2)}{1 + B + B^2 + B^3}} \qquad \text{V}$$

<u>General Solution</u>

Equations III, IV and V are solutions for units employing 1, 2 and 3 effective theoretical plates respectively. These may be rewritten as follows:

for equation III

$$C_1 = \frac{C_\circ + V\ W_\circ\ (B^0)}{B^0 + B^1}$$

for equation IV

$$C_2 = \frac{C_\circ + V\ W_\circ\ (B^0 + B^1)}{B^0 + B^1 + B^2}$$

and for equation V

$$C_3 = \frac{C_\circ + V\ W_\circ\ (B^0 + B^1 + B^2)}{B^0 + B^1 + B^2 + B^3}$$

From the forms of the three rewritten equations, it is readily apparent that the general solution for a unit employing a tower of any given number, n, of effective theoretical plates is:

$$C_n = \frac{C_\circ + V\ W_\circ\ (B^0 + B^1 + B^2 ---- B^{n-1})}{B^0 + B^1 + B^2 ---- B^n}$$

For a drying unit, C_n may be designated as C. B^0 is of course = 1 and B^1 = B. The general equation above may be written therefore as:

$$\boxed{C = \frac{C_\circ + V\ W_\circ\ (1 + B + B^2 ---- B^{n-1})}{1 + B + B^2 ---- B^n}} \qquad \text{VI}$$

Simplified Solutions

Equation VI may be simplified by multiplying through by B-1 to give:

$$\boxed{C = \frac{C_\circ\ (B-1) + V\ W_\circ\ (B^n-1)}{B^{n+1}\ -1}} \qquad \text{VII}$$

Equation VII holds for all cases except for the special case of B = 1. Solution for this special case is obtained by a simple form of equation VI which is:

$$\boxed{\text{For } B = 1; \quad C = \frac{C_o + V\,W_o n}{n + 1}} \qquad \text{VIII}$$